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Climate of the Past

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Abstract. The Greenland Ice Core Chronology 2005 (GICC05) is a time scale based on annual layer counting of high-resolution records from Greenland ice cores. Whereas the Holocene part of the time scale is based on various records from the DYE-3, the GRIP, and the NorthGRIP ice cores, the glacial part is solely based on NorthGRIP records. Here we present an 18 ka extension of the time scale such that GICC05 continuously covers the past 60 ka. The new section of the time scale places the onset of Greenland Interstadial 12 (GI-12) at 46.9±1.0 ka b2k (before year AD 2000), the North Atlantic Ash Zone II layer in GI-15 at 55.4±1.2 ka b2k, and the onset of GI-17 at 59.4±1.3 ka b2k. The error estimates are derived from the accumulated number of uncertain annual layers. In the 40–60 ka interval, the new time scale has a discrepancy with the Meese-Sowers GISP2 time scale of up to 2.4 ka. Assuming that the Greenland climatic events are synchronous with those seen in the Chinese Hulu Cave speleothem record, GICC05 compares well to the time scale of that record with absolute age differences of less than 800 years throughout the 60 ka period. The new time scale is generally in close agreement with other independently dated records and reference horizons, such as the Laschamp geomagnetic excursion, the French Villars Cave and the Austrian Kleegruben Cave speleothem records, suggesting high accuracy of both event durations and absolute age estimates.

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1 Introduction

The deep ice cores retrieved in Antarctica and Greenland are becoming increasingly important for the understanding of past climate. The ice cores obtained in Antarctica have provided paleoclimatic records that cover more than 800 ka of climate history (Jouzel et al., 2007) whereas the Greenland ice cores roughly cover the last glacial cycle (North Greenland Ice Core Project members, 2004). In order to interpret the climatic signal provided by the ice cores and to enable comparison with other paleo-climatic records accurate time scales are crucial. Because of their high accumulation rates, the Greenland ice cores are well suited for obtaining a chronology based on annual layer counting of the last glacial cycle. In addition, the Greenland ice cores very strongly reflect the abrupt climatic shifts of the last glacial period, the Dansgaard-Oeschger events, and they contain many reference horizons that enable comparison to other paleo-archives.

The most widely applied Greenland ice core time scales are the Meese-Sowers GISP2 stratigraphic time scale (Meese et al., 1997) and the modeled "ss09sea" time scale that has been applied to the GRIP and NorthGRIP ice cores (Johnsen et al., 2001). Those time scales agree within 750 years back to 40 ka, but beyond this point the disagreement becomes several thousands of years. So far, there has thus been no consensus for the Greenland ice core time scales in the glacial period (Southon, 2004).

The NorthGRIP ice core covers the past 123 ka and provides the longest continuous Greenland paleo-climatic record (North Greenland Ice Core Project members, 2004). This period includes the Holocene, the last glacial period and the termination of the previous interglacial period, MIS 5e or

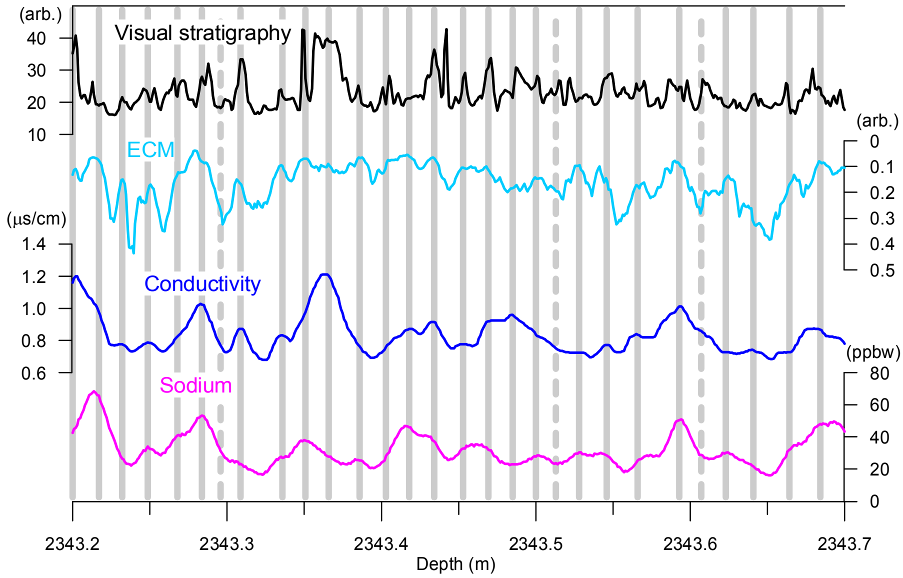

Fig. 1. Example of annual layer counting within GI-14. The records are visual stratigraphy grey scale, ECM, conductivity, and Na^+ concentration. (Uncertain) Annual layers are indicated by (dashed) grey vertical bars. Units of the grey scale and the ECM profiles are arbitrary but comparable to those in Fig. 2. The counting of this section is mostly based on the conductivity and Na^+ profiles because the other records are known to have multiple peaks within an annual layer during milder climatic periods.

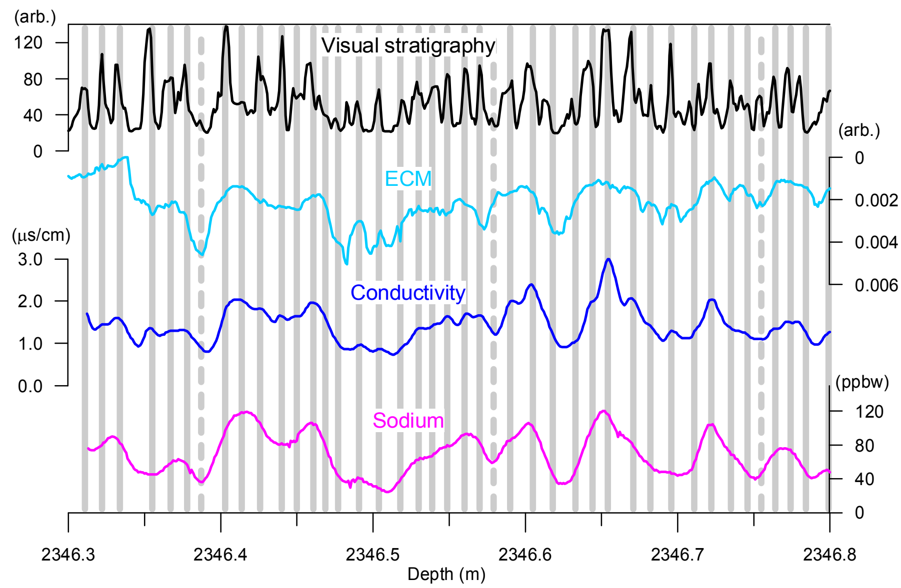

Fig. 2. Example of annual layer counting within the stadial preceding GI-14. Same legend as for Fig. 1. The counting of this section is mostly based on visual stratigraphy and ECM profiles which have the highest resolution.

the Eemian. The NorthGRIP accumulation history together with basal melting occurring at the drill site cause the annual layers in the glacial ice to be thicker than in other Greenland ice cores recovered so far. Flow models thus predict that the NorthGRIP annual layers are of the order of 1 cm at around 100 ka and the core, therefore, provides an outstanding opportunity to establish an absolute time scale for the entire last glacial cycle.

The Greenland Ice Core Chronology 2005 (GICC05) is a composite stratigraphic time scale based on multi-parameter counting of annual layers in three Greenland ice cores. The 0–7.9 ka section of the time scale is based on counting of annual layers in $\delta^{18}O$ and δD from the DYE-3, GRIP and NorthGRIP ice cores (Vinther et al., 2006). The 7.9–14.8 ka interval is established from Electrical Conductivity Measurements (ECM) of the solid ice and Continuous Flow Analysis

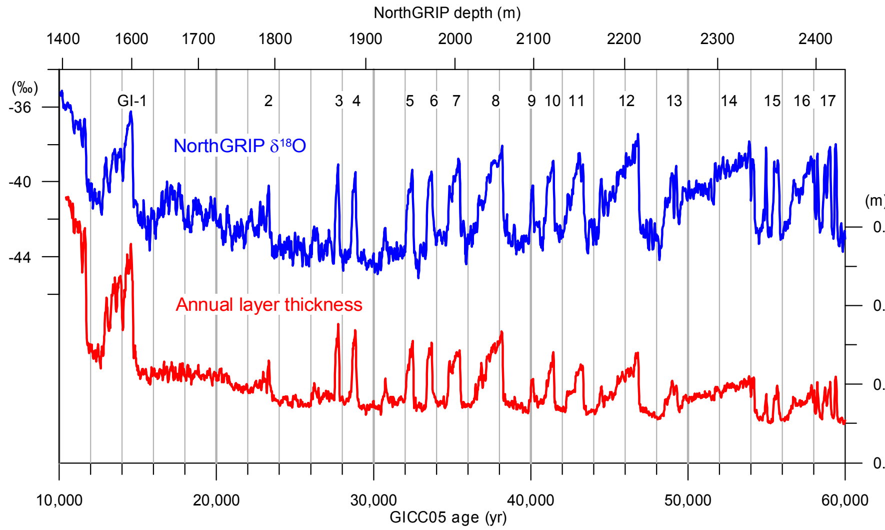

Fig. 3. The NorthGRIP δ^{18}O and the annual layer thickness profiles according to GICC05. The Greenland Interstadials (GI) are indicated.

records (CFA) of the GRIP and NorthGRIP ice cores (Rasmussen et al., 2006), whereas the 14.8–41.8 ka section is based on counting of annual layers in NorthGRIP ECM, CFA and visual stratigraphy data (Andersen et al., 2006; Svensson et al., 2006). GICC05 provides an uncertainty estimate based on the accumulated number of uncertain annual layers (see detailed discussion in Andersen et al. (2006) and Rasmussen et al. (2006)).

The GICC05 time scale was recently transferred to the GRIP and GISP2 ice cores which are tightly synchronized to the NorthGRIP ice core by reference horizons (Rasmussen et al., 2008). GICC05 is also transferred to the Greenland Renland ice core and to the Canadian Agassiz ice cores (Vinther et al., 2008). Furthermore, GICC05 has been applied for tuning of the Antarctic EDC3 and EDML1 ice core age models (Parrenin et al., 2007; Ruth et al., 2007) by matching of ^{10}Be profiles in the Holocene, by methane matching in the glacial termination, and by synchronization of ^{10}Be peaks associated with the Laschamp geomagnetic excursion at around 41 ka (Raisbeck et al., 2007).

Here we present the extension of the GICC05 back to 60 ka and we discuss comparison issues to other chronologies for the full 60 ka period. GICC05 ages are given in units of "b2k" with reference to the year AD 2000.

2 Methods

The annual layer counting of the 41.8–60.0 ka section of GICC05 is based on the same NorthGRIP data set that was applied to establish the 10.3–41.8 ka interval of the time scale and which is thoroughly described elsewhere (Rasmussen et al., 2006; Andersen et al., 2006). In summary, the applied continuous data series are the electrolytic melt water conductivity and the concentrations of the water-soluble ions Ca^{2+}, Na^{+}, NH_4^{+}, SO_4^{2-}, and NO_3^{-} (Bigler, 2004; Röthlisberger et al., 2000), the ECM (Dahl-Jensen et al., 2002) and the visual stratigraphy grey-scale profile (Svensson et al., 2005). The data series are almost complete with only very short gaps around breaks in the ice core. For the stadials the dating is based mainly on the records with the highest resolution, namely the visual stratigraphy, the ECM and the conductivity records, whereas the other records play a more important role during milder periods where the annual layers are thicker and the high-resolution records may have multiple annual peaks.

The annual layer thicknesses in the 41.8–60.0 ka section of the NorthGRIP ice core are comparable to those of the 23–41.8 ka section, and the applied counting technique is the same as that used for the younger parts of the record (Andersen et al., 2006; Rasmussen et al., 2006). Typical counting examples from just before and just after the onset of GI-14, respectively, are shown in Figs. 1 and 2. As for the younger part of GICC05, the error estimate is based on identification of "uncertain" annual layers that are counted as 1/2±1/2 year (Rasmussen et al., 2006). The accumulated error obtained by summing up the uncertain annual layers is called the Maximum Counting Error (MCE) and is regarded as a 2σ error of the time scale (MCE=2σ) (Andersen et al., 2006).

The entire 41.8–60 ka interval has been counted independently by two authors (KKA and AS) and the final dating is a compilation of those two preliminary records. The absolute difference between the two preliminary records is within the absolute error of the 41.8–60 section, although locally the difference sometimes exceeds the final counting error. There is potentially an additional uncertainty in the time scale arising from a systematic bias due to the assumed shape of annual layers that was used to interpret the data. Such a bias is, however, difficult to quantify and it is, therefore, not included

Table 1. GICC05 ages (with reference to year AD 2000, "b2k") and NorthGRIP depths for climatic events. The locations of the Glacial Interstadials (GI) are indicated in Fig. 3. "YD/PB" is the Younger Dryas – Preboreal transition. References: (1) Rasmussen et al. (2006), (2) Andersen et al. (2006).

Climate event	Age $\pm 1\sigma$ (yr b2k)	NorthGRIP depth (m)	Reference
YD/PB transition	11 703±50	1492.45	(1)
Onset GI-1	14 692±93	1604.64	(1)
Onset GI-2	23 340±298	1793.20	(2)
Onset GI-3	27 780±416	1869.12	(2)
Onset GI-4	28 900±449	1891.57	(2)
Onset GI-5	32 500±566	1951.66	(2)
Onset GI-6	33 740±606	1974.56	(2)
Onset GI-7	35 480±661	2009.45	(2)
Onset GI-8	38 220±725	2070.03	(2)
Onset GI-9	40 160±790	2099.62	(2)
Onset GI-10	41 460±817	2124.03	(2)
Onset GI-11	43 340±868	2157.49	This work
Onset GI-12	46 860±956	2222.30	This work
Onset GI-13	49 280±1015	2256.90	This work
Onset GI-14	54 220±1150	2345.52	This work
Onset GI-15	55 800±1196	2366.32	This work
Onset GI-16	58 280±1256	2402.55	This work
Onset GI-17	59 440±1287	2420.44	This work

Table 2. GICC05 ages, NorthGRIP depths, and radiometric ages for volcanic and geomagnetic reference layers. ^{14}C ages are uncalibrated. References: (1) Rasmussen et al. (2006), (2) Svensson et al. (2006), (3) See references in Rasmussen et al. (2007), (4) Davies et al. (2008); Wastegård et al. (2006) (5) Benson et al. (2003), (6) Wastegård et al. (2006); Rasmussen et al. (2003), (7) Guillou et al. (2004), and (8) Southon (2004).

Reference horizon	GICC05 age $\pm 1\sigma$ (yr b2k)	NorthGRIP depth (m)	Radiometric age $\pm 1\sigma$ (yr BP)	GICC05 reference	Radiometric method and reference
Saksunarvatn tephra	10 347±45	1409.83	9000±100	(1)	C-14 (3)
NAAZ I / Vedde tephra	12 171±57	1506.14	10 330±65	(1)	C-14 (3)
FMAZ II / Fugloyarbanki tephra	26 740±390	1848.05	23 100±250	(2)	C-14 (4)
Mono Lake event	34 250±626	1982.70	28 620±300	This work	C-14 (5)
FMAZ III/33 ka ^{14}C tephra	38 122±723	2066.95	33 000±1000	This work	C-14 (6)
Laschamp event	41 250±814	2118.66	40 400±1000	(2)	Ar-Ar (7)
NAAZ II/Z2 tephra	55 380±1184	2359.45	54 500±1000	This work	Ar-Ar (8)

in the uncertainty estimates given (see detailed discussion of error estimate in Rasmussen et al. (2006)).

3 Results

Figure 3 shows the NorthGRIP δ^{18}O and annual layer thickness profiles according to the new time scale. To first order there is a clear correspondence between climate and annual layer thickness throughout the 60 ka period. However, the high frequency variation in the layer thickness profile appears more dampened than in the δ^{18}O profile. Generally, in the 41.8–60 ka interval the annual layers are 1–1.5 cm thick in cold glacial stadials and 1.5–2.5 cm thick in mild interstadials. The MCE for the 41.8–60 ka section is 950 years or 5% which is similar to that of the 14.8–41.8 ka section.

Table 1 gives the GICC05 ages of the onsets of the glacial interstadials that are determined visually from the steepest part of the δ^{18}O profile. Table 2 gives GICC05 and corresponding radiometric ages of important reference horizons. In the following we compare GICC05 to other independent time scales and reference horizons.

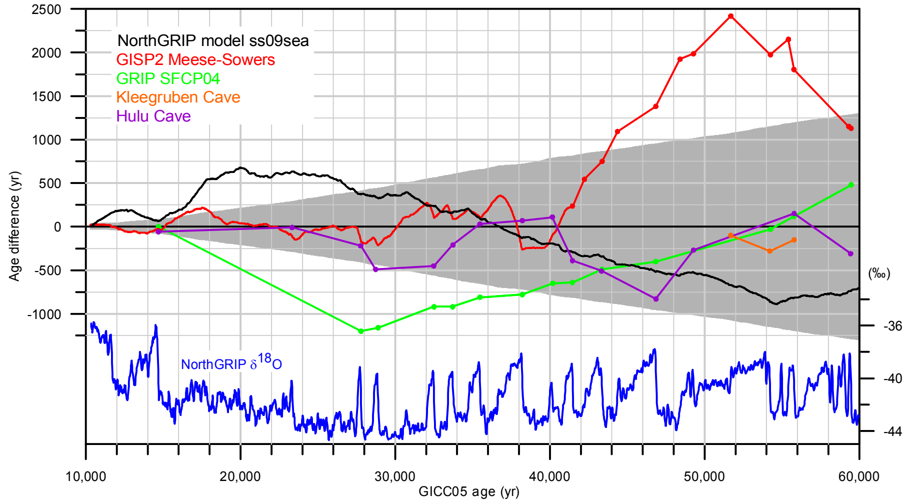

Fig. 4. Comparison between GICC05 and independently dated records: the NorthGRIP model time scale "ss09sea" (North Greenland Ice Core Project members, 2004), the GISP2 time scale (Meese et al., 1997), the GRIP SFCP04 time scale (Shackleton et al., 2004), the Kleegruben Cave record (Spötl et al., 2006), and the Hulu Cave record (Wang et al., 2001). A positive value means that the record is younger than GICC05. The grey shaded area represents the GICC05 counting uncertainty (1σ). The GICC05 and the GISP2 records are linked via volcanic reference horizons and other match points back to 32.5 ka (Rasmussen et al., 2006; Rasmussen et al., 2008) and by matching of the rapid shifts in δ^{18}O in the remaining part. The Hulu and Kleegruben Cave records are matched as indicated in Figs. 5 and 6.

4 Comparison to ice core time scales

One of the most frequently applied Greenland ice core chronologies is that of the GISP2 ice core referred to as the Meese-Sowers time scale (Alley et al., 1997; Meese et al., 1997). The glacial part of this time scale is based on annual layer counting of visual stratigraphy, laser-light scattering, and ECM, and it has an estimated error of 2% back to 40 ka and 5–10% back to 57 ka. For the past 40 ka, there is a good long-term accordance between the GICC05 and the GISP2 time scales (Fig. 4). The major discrepancy in this time interval is due to an inconsistent climate (δ^{18}O) – accumulation relation for the GISP2 time scale, which generally causes the interstadials to appear too long and the stadials to appear too short (Svensson et al., 2006). Beyond 40 ka, however, the GICC05 and the GISP2 time scale start to deviate very importantly and reach a maximum difference of 2.4 ka at around 52 ka, which then decreases to 1 ka at 60 ka. The GISP2 chronology thus contains respectively 20% more and 20% fewer annual layers in those two intervals compared to GICC05. We will not attempt to identify the cause of this discrepancy, but we notice that no other chronology shows a similar behavior in this period.

The modeled NorthGRIP "ss09sea" time scale is based on an empirical δ^{18}O – accumulation relationship, an ice flow model, and two fixed points at 11.55 and 110 ka, respectively (Johnsen et al., 2001). The model also takes into account past changes in seawater δ^{18}O due to changes in global ice volume and the basal melt at NorthGRIP (Andersen et al., 2006). Except for a significant divergence in the 15–18 ka interval, GICC05 and "ss09sea" agree reasonably well throughout the 60 ka with a maximum age difference of 900 yrs (Fig. 4). This suggests that the general approach of the model holds throughout the 60 ka, except for the 15–18 ka interval. Nevertheless, smaller differences in the annual layer thickness profiles of GICC05 and "ss09sea" can be identified both in the Holocene and in the deglacial period (Rasmussen et al., 2006) as well as in both cold and milder periods in the glacial (Andersen et al., 2006; Svensson et al., 2006). Such differences can be due to errors in the counted time scale or deviations from the δ^{18}O – accumulation relationship that is applied in the model. A more comprehensive comparison between the two time scales will be approached in future work.

The SFCP04 time scale is based on the marine core MD95-2042 that is ^{14}C calibrated back to 40 ka using Fairbanks et al. (2005) and matched to the Hulu Cave record (see below) at certain fixed points beyond 40 ka (Shackleton et al., 2004). Further, SFCP04 was transferred to the GRIP core by wiggle-matching of δ^{18}O profiles. The GRIP SFCP04 time scale disagrees with GICC05 and with several other records at the onset of GI-3 by more than 1 ka, but the difference vanishes towards 55 ka, where SFCP04 is calibrated by the Hulu Cave record (Fig. 4). As described in Svensson et al. (2006) the most likely reason for this difference is that the fix point used for SFCP04 at the onset of GI-3 is too old (by about 1 ka).

5 Comparison to cave records

A growing number of absolutely dated speleothem records from caves around the world are becoming available. Many

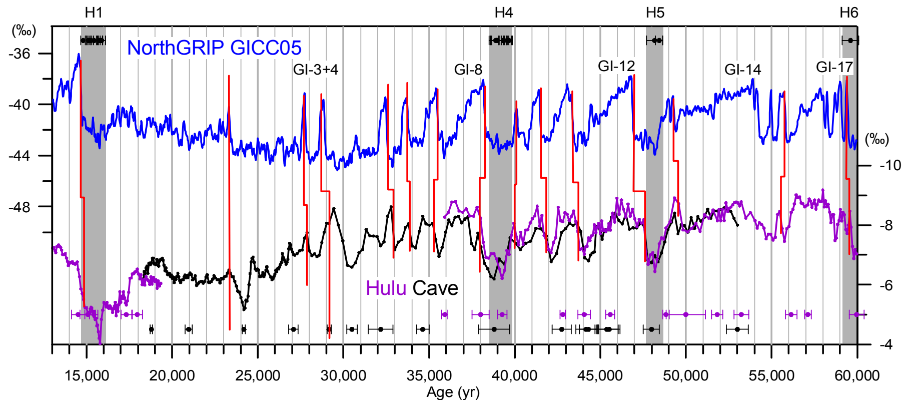

Fig. 5. The NorthGRIP and the Hulu Cave δ^{18}O records on their respective time scales. The red lines indicate the points of comparison applied in Fig. 4. The absolutely dated control points for the Hulu Cave are shown in the lower part of the figure (Wang et al., 2001). The position of the stadials associated with but not identical to the Heinrich events H1, H4, H5, and H6 are indicated as grey vertical bars according to the dating of Brazilian speleothems shown in the top part of the figure (Wang et al., 2004).

of those records have climate records resembling those of the ice core records, which enable comparison under the assumption that the climatic shifts recorded at the two sites occurred simultaneously. This assumption is likely to be valid on the time scales considered here.

The Chinese Hulu Cave stalagmite record (Wang et al., 2001) has become widely accepted as a Northern Hemisphere template for the last glacial period. The stalagmite is ^{230}Th dated at a number of depths and the time scale is linearly interpolated between those depths. It is worth noticing that the NorthGRIP and the Hulu Cave records have very different physical characteristics: whereas the 10–60 ka section of the ice core record represents 900 m of annual layers, the corresponding sections in the stalagmites span less than one meter. Because of the absolute dating, the Hulu Cave record has high long-term accuracy, while the duration of shorter time intervals may be less accurately determined due to analytical errors and errors introduced by interpolation. For the stratigraphic ice core time scale the situation is just the opposite. Whereas the absolute ages are potentially inaccurate due to the incremental nature of the ice core dating uncertainty, the duration of shorter periods and events is known with high accuracy.

The Hulu Cave and the NorthGRIP δ^{18}O profiles can be compared in several ways. Here, we match up the onsets of the glacial interstadials, as they are the most clearly defined events, at least in the ice core record (Fig. 5). The exception is GI-4, which has very different shapes in the two records. The Hulu cave record has, however, an absolute Th age close to the top of GI-4, which we apply as reference horizon because it can be well correlated to the ice core record. In most other cave records, the shape of GI-4 is narrower than in the Hulu Cave record, as for example the Brazilian Botuverá cave record that places the onset of GI-4 around 29.5 ka (Wang et al., 2006).

It is encouraging to observe the rather good overall age scale agreement between the Hulu Cave and the NorthGRIP records despite their different nature (Figs. 4 and 5). The largest age difference of 800 years appears at the onset of GI-12, but otherwise the two time scales agree within 500 yrs throughout the 60 ka period. Such a good agreement would be unlikely if one of the records had a significant dating error. Because of the relatively coarse resolution of the Hulu Cave time scale and because we do not know if the two records are synchronous, we will not attempt to explain the deviation of individual points at this stage. A new high-resolution δ^{18}O profile and a new high-precision dating of the Hulu Cave record are under way, which will allow for a more detailed comparison.

A recent speleothem record from the Austrian Kleegruben Cave provides a high-resolution record of the 50–57 ka period covering GI-13 to GI-16 (Spötl et al., 2006). For the events GI-14 and GI-15 that are very well resolved in the speleothem record there is an excellent match to GICC05 of less than 300 yrs difference (Figs. 4 and 6). Towards the ends of the speleothem, however, the comparison to the ice core indicates that the dating error of the speleothem may be larger than the stated radiometric uncertainties, which is probably due to the very low growth rate in the uppermost part.

The stadials preceding GI-1, 8, 12, and 17, which are associated with the Heinrich events H1, H4, H5, and H6, have been linked to wet periods in Brazil that are constrained by absolutely dated speleothems (Wang et al., 2004). Under the assumption that it is indeed the same periods that are recorded in Greenland and in Brazil those speleothem ages support the long-term GICC05 dating (Fig. 5).

The French Villars Cave speleothem records discontinuously cover the interval 21–82 ka (Genty et al., 2003; Genty et al., 2005). Although the records are not always directly

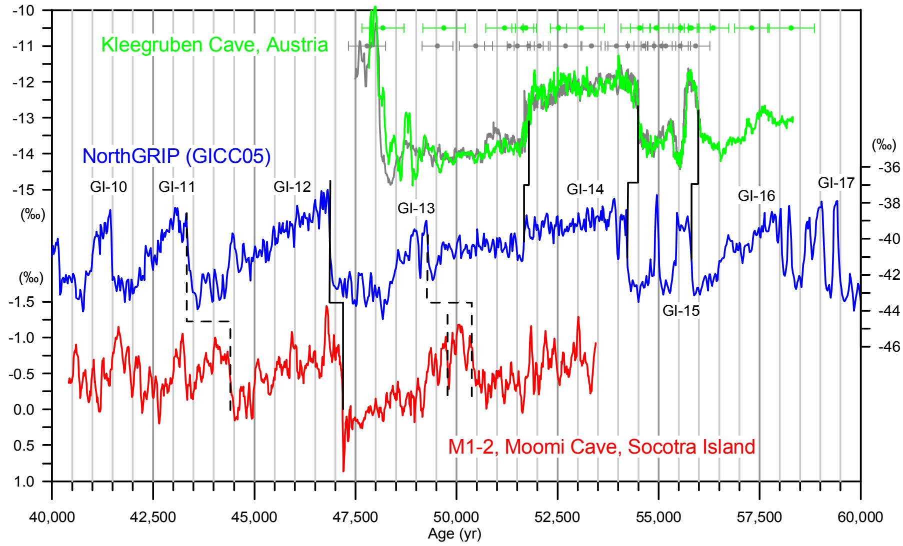

Fig. 6. The NorthGRIP δ^{18}O compared to the Austrian Kleegruben Cave (Spötl et al., 2006) and the Socotra M1-2 Moomi Cave (Burns et al., 2003, 2004) δ^{18}O records on their respective time scales. Black lines indicate a possible matching of the records. The absolutely dated control points for the Kleegruben Cave are shown in the upper part of the figure with 2σ error bars.

comparable to the Greenland record, several interstadial onsets are well defined. The onset of GI-12 is well constrained to 46.6±0.5 ka, which is in excellent agreement with GICC05. The onset of GI-17 is constrained both by the Villars Cave and by new Chinese speleothem records from Shanbao Cave (Xia et al., 2007) and Xinya Cave (Li et al., 2007), which all support the GICC05 chronology in this time interval.

The Socotra Island stalagmite record M1-2 from Moomi Cave (Burns et al., 2003, 2004) appears more difficult to fit within the pattern (Fig. 6). Although the M1-2 age of the onset of GI-12 agrees with GICC05 within 350 yrs, the onsets of adjacent interstadials deviate more than 1 ka from GICC05. This is difficult to combine with the well-constrained event durations of the ice core chronology.

6 Cosmogenic nuclide records

Ice core time scales can be compared to tree ring chronologies through comparison of ice core ^{10}Be and tree ring ^{14}C records. Both ^{10}Be and ^{14}C are cosmogenic nuclides that share a common signal which allows for detailed comparison (Muscheler et al., 2000; Finkel and Nishiizumi, 1997). A recent such comparison suggests that GICC05 is 65 years older than the tree ring chronology at the Younger Dryas – Holocene transition and that there is an inconsistency between GICC05 and the IntCal04 calibration curve at the onset of the Younger Dryas (Muscheler et al., 2008).

Changes in the geomagnetic field are expressed in the ^{10}Be and ^{36}Cl records of ice cores. Within the 60 ka time frame there are two major geomagnetic events, namely the Mono Lake and the Laschamp events (Table 2, Fig. 7). The most prominent of those is the Laschamp event that is located around GI-10. This event provides an important link between Greenland and Antarctic ice cores that can be synchronized very accurately through comparison of ^{10}Be records (Raisbeck et al., 2007). GICC05 agrees within error estimates with independent radiometric ages of the Laschamp event (Guillou et al., 2004; Ton-That et al., 2001; Svensson et al., 2006). The Mono Lake event that is situated between GI-6 and GI-7 is most strongly expressed in the Greenland ^{36}Cl record (Wagner et al., 2000). This event has been dated in the Pyramid Lake Basin of Nevada to 28 620±300^{14}C yr BP (Benson et al., 2003) which compares well to GICC05 when calibrated by the suggested calibration curve of Fairbanks et al. (2005).

7 Tephra horizons

Tephra layers provide a robust method of linking different paleo-records. The number of tephra layers identified in the Greenland ice cores is rapidly increasing (Zielinski et al., 1997; Mortensen et al., 2005), but not all of the ice core horizons have been found in marine or terrestrial records and vice versa. In the 10–60 ka period there are five tephra layers that provide important tight links to marine and terrestrial records in the North Atlantic region (Table 2). Of those the Saksunarvatn tephra, the Vedde tephra, and the Fugloyarbanki tephra layers have been discussed elsewhere (Rasmussen et al., 2007; Svensson et al., 2006; Davies et al., 2008).

A newly identified tephra layer in the ice cores, the so-called Faroe Marine Ash Zone III (Wastegård et al., 2006)

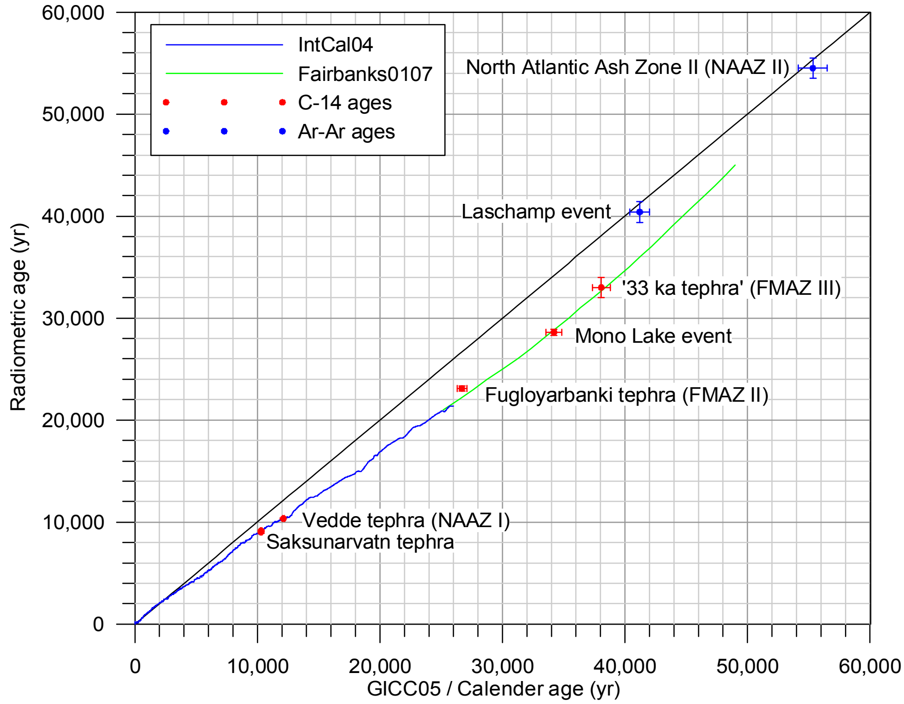

Fig. 7. Comparison between GICC05 and independent ^{14}C and Ar-Ar ages of volcanic and geomagnetic reference horizons identified in the NorthGRIP ice core. The ^{14}C calibrations of IntCal04 (Reimer et al., 2004) and Fairbanks0107 (Fairbanks et al., 2005) are shown. Error bars are 1σ. In case of agreement between radiometric ages, ^{14}C calibration curves, and ice core ages, the ^{14}C data points should fall on the ^{14}C calibration curves, whereas Ar-Ar data points should fall on the 1:1 line. See Table 2 for references.

(also referred to as the "33 ka ^{14}C" layer), is situated at 2066.95 m depth in the NorthGRIP ice core. Although the age estimate for this tephra is based on interpolation of AMS radiocarbon dates in marine cores in the Faroes region (Rasmussen et al., 2003), this estimate falls well onto a suggested ^{14}C calibration curve (Fairbanks et al., 2005) when compared to GICC05 (Fig. 7). It should be noted that there is an important scatter among the various datasets underlying the suggested ^{14}C calibration curves around this time interval (van der Plicht et al., 2004).

One of the most widespread tephra layers in the North Atlantic region is the North Atlantic Ash Zone II or "Z2" layer that appears right at the decline of GI-15. The layer is clearly visible as a centimeter thick layer in several Greenland ice cores. This tephra has been assigned a wide range of ages in the literature (Austin et al., 2004), but a recent Ar-Ar age of 54.5±1.0 ka BP (Southon, 2004) agrees very well with GICC05 (Fig. 7).

8 Conclusions

A new Greenland stratigraphic ice core chronology (GICC05) has been extended by 18 ka to continuously cover the past 60 ka. The new section of the time scale covers the glacial interstadials 11 to 17 and includes the widespread North Atlantic Ash Zone II in interstadial 14. The maximum counting error of the time scale is on average 1% in the Holocene and 5% in the Glacial.

Comparison of GICC05 to existing Greenland ice core time scales reveals a major discrepancy with the Meese-Sowers GISP2 time scale of up to 2.4 ka in the 40–60 ka interval. In the same period GICC05 and the modeled "ss09sea" time scale show differences in absolute ages of up to 800 yrs. The GRIP SFCP04 time scale and GICC05 deviate more than 1 ka at around 28 ka but they agree well at 60 ka.

Under the assumption that the climatic events observed in the Greenland stable isotope profiles are synchronous with those seen in Chinese Hulu Cave record, GICC05 agrees with the Hulu Cave time scale within 800 yrs throughout the 60 ka period. There is a very good match between GICC05 and the Austrian Kleegruben Cave around GI-14/15 and there are good matches to the French Villars Cave at the onsets of GI-12 and GI-17. The Socotra Moomi Cave record (M1-2) agrees well with GICC05 at onset of GI-12 but does otherwise not compare well to the ice core record. In fact, all of the cave records contain some features for which the comparison to the ice core profile is less obvious.

Five tephra layers and two geomagnetic events identified in the 60 ka section of the ice cores have been dated independently by ^{14}C or Ar-Ar. Generally, the dating of those reference horizons agree with GICC05 within the error estimates, but several of the ages are based on ^{14}C calibration curves, marine reservoir ages, or they are not very well documented (NAAZ II tephra layer).

We notice that most independent chronologies and absolutely dated reference horizons in the 0–60 ka period now seem to agree within hundreds rater than thousands of years. The general agreement between the new Greenland chronology and many other independent time scales and reference horizons excludes the possibility of a significant hiatus in the Greenland ice cores and it supports that GICC05 has no significant long-term bias.

The use of ice core cosmogenic isotope records – in particular ^{10}Be – has proven very efficient as a tool for synchronization and comparison of paleo-records. Recently, the Greenland ^{10}Be records have allowed for a detailed comparison to tree ring chronologies and for a synchronization of the Laschamp event in Greenland and Antarctic ice cores. The method could potentially be applied throughout the glacial period at very high resolution, provided there are more high-resolution ice core ^{10}Be and ^{36}Cl profiles available.

For the future, a lowering of the error estimate of the Greenland ice core chronology can be expected when new high-resolution records become available from the NEEM ice core drilling that will soon be initiated. Although the annual layers in the Greenland ice cores do get below critical 1 cm thickness beyond 60 ka, the annual layers are still countable both in Greenland and in high-accumulation Antarctic ice cores at least back to 80 ka provided the records have sufficiently high resolution.

The GICC05 time scale is available at www.iceandclimate.dk and at the World Data Centre for Paleoclimatology.

Supplement:
http://www.clim-past.net/4/47/2008/
cp-4-47-2008-supplement.zip

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